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REPORT

**UHF TELEVISION:
impairments to domestic reception with
envelope and synchronous detectors caused by
carrier phase perturbation in relay transmitters**

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**UHF TELEVISION: IMPAIRMENTS TO DOMESTIC RECEPTION WITH ENVELOPE
AND SYNCHRONOUS DETECTORS CAUSED BY CARRIER PHASE
PERTURBATION IN RELAY TRANSMITTERS**

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Summary

The effects of amplitude-dependent phase modulation in the travelling-wave-tube amplifiers of u.h.f. television relay transmitters on the quality of the picture at the receiver are considered theoretically, and the results of relevant measurements are reported, for receivers using envelope detectors and synchronous demodulators.

It is shown that the major impairment produced by this phase modulation takes the form of a sound/chrominance beat which is generally below the threshold of perceptibility unless more than two or three relay transmitters are operated in tandem.

Provided that the total phase modulation in the transmitter chain is controlled so that this beat pattern does not rise above an acceptable level, no other impairment to the received picture will be perceptible. This applies equally to receivers with conventional envelope detectors and those with the type of synchronous demodulators in current use.

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UHF TELEVISION: IMPAIRMENTS TO DOMESTIC RECEPTION WITH ENVELOPE AND SYNCHRONOUS DETECTORS CAUSED BY CARRIER PHASE PERTURBATION IN RELAY TRANSMITTERS

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1. Introduction

Developments in the u.h.f. transmitter network over recent years have included proposals for chains of relay transmitters, perhaps involving four or more relays in tandem. Many of these relay stations will be of a type in which the signal from the previous transmitter is received on a suitable aerial, transposed in frequency without demodulation and amplified, using a separate travelling-wave-tube (t.w.t.) amplifier for each programme signal. The outputs from the amplifiers are combined and radiated from a common transmitting aerial. The distortions and intermodulation components in the output from the final link in the chain are cumulative effects of all of the relays.

Travelling-wave-tube amplifiers, unlike klystron amplifiers, have excellent amplitude linearity in normal operation but they fall short of the ideal in that the delay of the signal through the amplifier depends on the momentary signal power, leading to amplitude-dependent phase modulation of the signal. Bandwidth limitation, in both the transmitter and the receiver, suppresses some of the sidebands associated with this phase modulation but leaves others within the pass-band of the receiver; in particular, a sound/chrominance beat component at 1.57 MHz above the vision carrier.

Video demodulators in television receivers have in the past been of a simple type using a semiconductor diode and responding to the amplitude modulation of the applied signals but not to the phase modulation. However, receivers are now available that incorporate integrated-circuit synchronous demodulators¹ in which the demodulating carrier is obtained by bandwidth restriction and amplitude limitation of the received signal. The main advantage of this system appears to be a reduction of the cost of the receiver by requiring less gain in the i.f. stages. However, the bandwidth restriction of the carrier regenerating section of the integrated circuit could prevent the phase of the demodulating subcarrier from following that of the signal, making the demodulator respond to phase modulation.

An investigation was therefore started into the extent to which receivers incorporating synchronous demodulators are compatible with chains of relay transmitters using t.w.t. amplifiers.

2. Travelling-wave-tube characteristics

2.1. Power-dependent phase perturbations

A travelling-wave-tube amplifier consists² essentially of a focused electron beam, surrounded by a conductor which is wound in the form of a helix and to which a d.c.

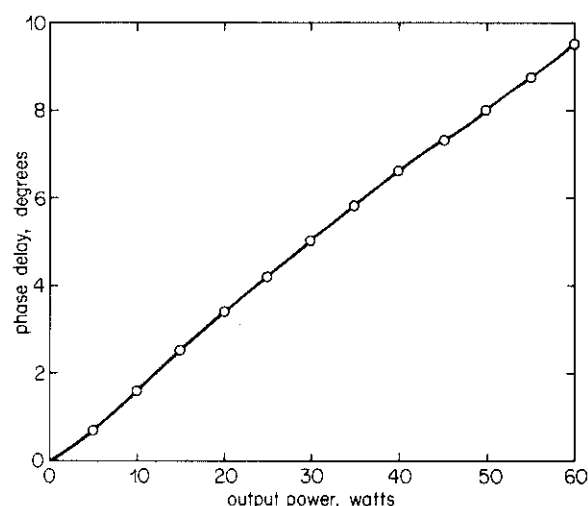


Fig. 1 - Phase delay of a travelling-wave tube at 500 MHz

accelerating potential is applied. The r.f. signal which is to be amplified travels along this helical conductor, the electromagnetic field interacting with the electron beam and causing some electrons to be accelerated and others retarded. The overall result is that some of the energy of the electrons, derived from the applied d.c. potential, is transferred to the field, giving amplification of the signal. The absorption of energy from the beam reduces the mean velocity of the electrons which in its turn results in phase retardation of the output from the amplifier.

Fig. 1 shows an example of the measured relationship between r.f. output power and phase delay, at a frequency of 500 MHz, for one type of travelling-wave-tube used in BBC u.h.f. relay transmitters. A fuller theoretical treatment and a calculation of the phase delay is given in an Appendix (Section 8.1). The results of calculation agree closely with those of the measurements given in Fig. 1.

2.2. Derivation of intermodulation products

For the purposes of calculation let us assume that the r.f. television signal consists of only three components of constant amplitude, namely the vision and sound carriers and the upper sideband corresponding to the colour sub-carrier. The power in the envelope or vector sum of these three steady signals is calculated in an Appendix (Section 8.2) and is shown to possess a constant component plus alternating components at three frequencies; these latter correspond to the three differences between the three primary signal frequencies. Fig. 1 shows that the phase perturbation is closely proportional to the signal power; each of the three primary signal may therefore be treated

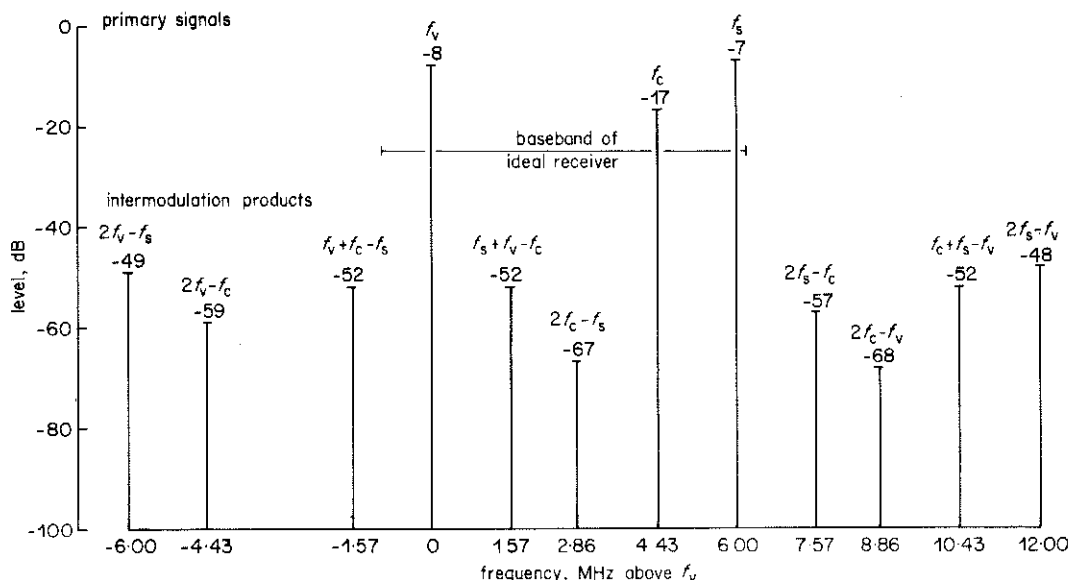


Fig. 2 - Spectrum of intermodulation products caused by power-dependent phase shift in a travelling-wave tube during the three-tone test

as being separately phase modulated by each of the three difference frequencies. For small perturbations, one need consider only the first order sideband of each modulation process, leading to a total of 18 sideband components. Of these, 6 occur as coincident pairs at the frequencies of the primary signals and simply modify their levels and six more appear as coincident pairs at three other frequencies, leaving a spectrum containing nine new components, as shown in Fig. 2. Of these nine new components only two will be within the passband of a properly tuned receiver, namely those at 1.57 MHz and 2.86 MHz above the vision carrier. These will each give rise to both amplitude and phase modulation of the vision carrier. It is shown in an Appendix (Section 8.2) that only one of these two components is important in practice; this is the component spaced at the sound/chrominance difference frequency, 1.57 MHz, above the carrier, thus causing a 1.57 MHz interference component in the demodulated video signal.

2.3. The three-tone test for intermodulation

A standard test for television transmitters consists of applying three steady signals simultaneously.³ The signal frequencies are those of the vision carrier, the upper sideband component representing the colour subcarrier and the sound carrier; the levels of the three signals are, respectively, -8 dB, -17 dB and -7 dB with respect to the peak sync level of the applied television signal. These chosen levels are compared with those corresponding to a saturated colour bar picture in Section 3.1.1. In this test condition the level of the sound/chrominance intermodulation product is measured and its maximum value is at present specified as being -52 dB, with respect to peak sync level.

3. Theoretical impairment to reception

3.1. Sound/chrominance beat pattern

3.1.1. Comparison of test signal and colour bar signal

It is useful to choose a highly saturated picture as a

reference in assessing the effects of sound/chrominance intermodulation and the 100% colour bar signal was used for this purpose.

Fig. 3 shows the envelope of the r.f. 100% colour bar signal after passing through the vestigial sideband filter at a transmitter; this is different from the more familiar envelope obtained after the v.s.b. filter in an ideal receiver. The relative levels of vision, colour and sound signals are tabulated opposite each colour bar, together with the levels of the sound/chrominance intermodulation product which will be produced by a transmitter which just satisfies the three-tone test specification.

3.1.2. Inference of subjective impairment

Since we know the subjective impairment caused by an interfering c.w. signal⁴ we can deduce the impairment caused by the sound/chrominance beat. C.W. interference at 1.57 MHz above the vision carrier frequency, with no special control of the frequency and at a level of 45 dB below peak sync level, will give an impairment grade which is generally agreed to be grade 3.5 on the 6-point scale.⁵ Allowing 6 dB per grade, the limit of perceptibility (grade 1½) will correspond to a level of -57 dB. However, the sound/chrominance beat has a certain degree of frequency control owing to the maintenance of the sound/vision frequency difference at 6 MHz - 400 Hz ± 500 Hz. The benefit of this specification in reducing the impairment from the sound/chrominance beat has been demonstrated⁶ and allows an increase in the level of intermodulation of about 6 dB, leading to a figure of -51 dB for grade 1.5 impairment. This latter statement must be interpreted with caution as strictly it applies only to average pictures with uniform interference; it is nevertheless useful to consider it as applying to pictures containing large areas of saturated colour.

Comparing the deduced level of -51 dB for the thres-

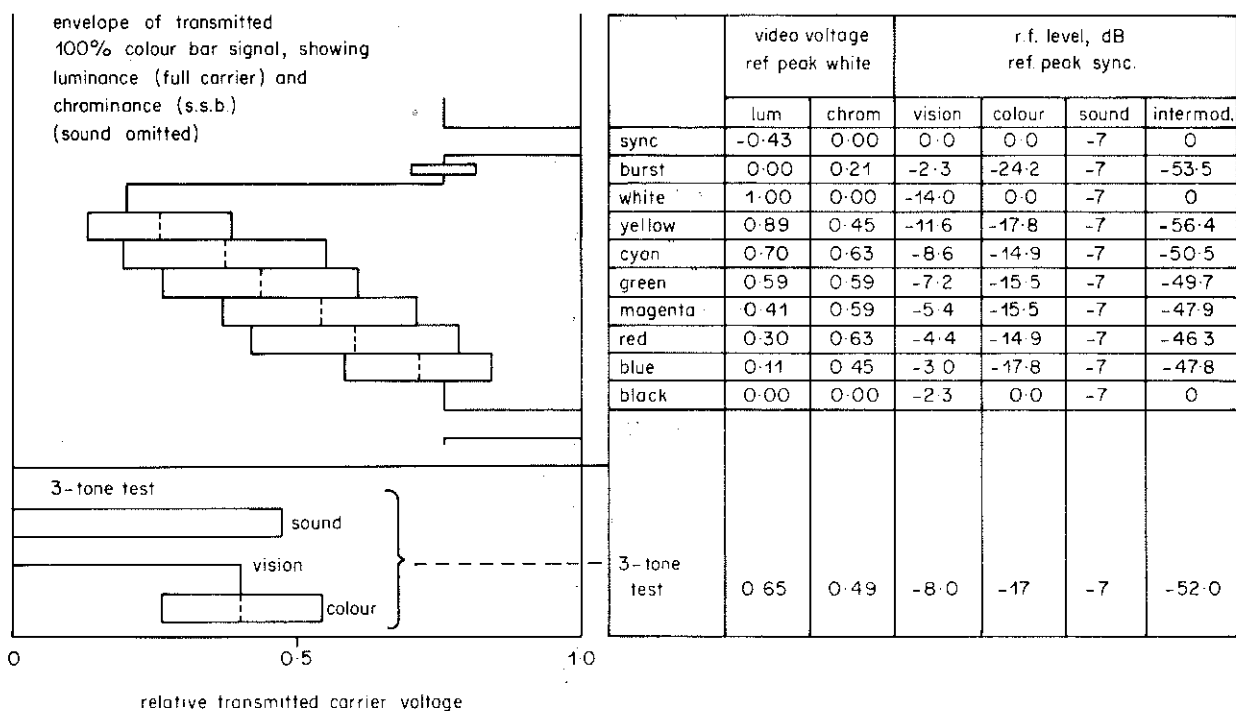


Fig. 3 - Levels of sound/chrominance intermodulation produced by 100% colour bar signal in a travelling-wave tube

hold of perception with the levels appropriate to 100% colour bars, given in Fig. 3, the high-luminance colours give approximately the same level of intermodulation. Although, for example, saturated red gives a 5 dB higher level, the impairment is probably reduced to some extent by the lower luminance value. It is concluded from this argument that a technical observer will just perceive the sound/chrominance beat on 100% colour bars when the transmission system gives a level of -52 dB intermodulation during the three-tone test.

3.2. Receivers with synchronous demodulators

3.2.1. Luminance errors

With the advent of domestic receivers with integrated circuit i.f. demodulators employing synchronous detection it was anticipated that new forms of picture impairment might arise. Such receiver circuits would be expected to be more linear, and therefore less prone to the production of sound/chrominance beat and sound 'buzz' within the receiver, but it was thought that this might be more than offset by the inherent sensitivity to any inadvertent phase modulation of the r.f. signal.

In one common type of integrated circuit demodulator¹ the incoming i.f. signal is filtered by a single resonant circuit tuned to the vision i.f.; the voltage across this circuit is limited in amplitude by two diodes and the filtered and limited carrier is then multiplied by the original i.f. signal to give a composite video and intercarrier sound output. The Q factor of the carrier filter determines the rate at which the regenerated carrier can follow any phase change. Although Q factors of 40 or 50 are common in the simpler types of circuit, this factor could easily rise to

500 or more if phase-lock loop techniques are employed.

Waveform distortion would be greatest after a transition from a low carrier envelope level to a high one, e.g. after a white-to-black step, and would, as shown in an Appendix (Section 8.3), amount to an undershoot of about 2% for a chain of 5 tandem relays, each having the characteristics of Fig. 1, and a total phase shift of about 10 degrees at black level. This would be subjectively perceptible as a streaking only if the Q factor of the carrier filter approached 200, giving a recovery time constant of about 2 μ s.

3.2.2. Synchronising errors

A second form of impairment could occur in extreme conditions as a timing defect leading to line-pulling when the right-hand edge of the picture is white. In these circumstances a high carrier-filter Q could cause an undershoot and distortion of the leading edge of the synchronising pulse. For five relays in tandem (17 degrees phase shift at sync level) the maximum defect would lead to an undershoot of about 18% of the sync pulse height and is not likely to cause line pulling.

4. Experimental results

4.1. Phase and intermodulation in a travelling-wave tube

An u.h.f. travelling-wave tube was operated under the conditions described in an Appendix (Section 8.1). With a c.w. input signal, the power output and phase shift were measured; these are shown in Fig. 1. The standard three-tone test signal, as described in Section 2.3, was then

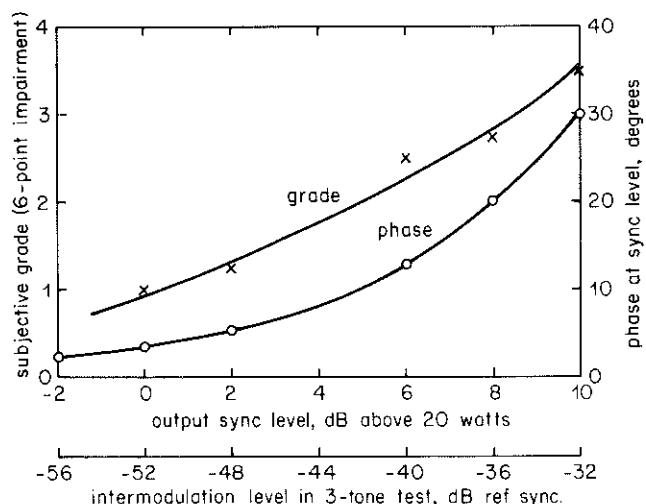


Fig. 4 - Grade of impairment of 100% colour bar signal and phase shift versus output power for a single travelling-wave tube

applied with the three signals giving output powers of -8, -17 and -7 dB respectively referred to a power output level of 20 watts. The intermodulation product at the sound/chrominance beat sideband frequency was then measured with a spectrum analyser and found to be -52 dB. At other reference power levels, the relative intermodulation level was found to follow a square law as expected from the theory and as is shown on the lower horizontal scale of Fig. 4.

4.2. Visibility of sound/chrominance beat

Three domestic colour television receivers, one with an envelope detector and two with synchronous demodulators of the same type, were fed in turn from the attenuated signal from the travelling-wave tube. First, with Test Card modulation, in order to assist proper adjustment of each set, and then with a 100% colour bar signal, modulated onto a carrier according to the normal operating specification. A subjective assessment of the grade of impairment of the colour bar signal was made on each receiver for a variety of t.w.t. output power levels, adjusting the attenuation to preserve the received signal level at about 3 millivolts e.m.f. The mean grades are shown in Fig. 4.

In view of the fact that these tests were made with one observer and on a limited range of picture material, the results give only an approximate indication of the level of impairment produced. Definitive results would require more thorough testing with a large number of observers and a wide range of programme material. There was no significant difference in performance between the receiver using envelope detection and those using synchronous demodulation. A small adjustment to the tuning of one receiver was made in order to remove some self-generated sound/chrominance beat which was apparent at a power level well below the normal operating level. The visibility of intermodulation products generated in the t.w.t. was

observed to be virtually independent of receiving tuning. The results show that the intermodulation caused by phase perturbations in a single t.w.t. is imperceptible at the operating conditions specified by the three-tone test, even for 100% colour bar signals. If for example, five similar t.w.t.s were operated in tandem and the individual phase modulation contributions added arithmetically, the intermodulation level would rise by 14 dB, corresponding to the impairment caused by a single t.w.t. when overdriven by 7 dB. However, the individual contributions from the members of a chain of relays may not be exactly in phase so that the total resulting impairment may be less.

4.3. The visibility of luminance and synchronising errors

Under the conditions described in Section 4.2 the received pictures were examined, using test-card modulation, for any systematic increase in undershoots and distorted verticals as the power level was increased up to 10 dB overload. No systematic luminance or timing defects were observed.

5. Discussion of results

The phase shift in a typical travelling-wave tube, its relation to the power level and the degree of intermodulation produced in the received signal have been measured and are in good agreement with theoretical predictions. The perceptibility of the sound/chrominance beat pattern caused by intermodulation of colour bar components is also in reasonable agreement with the results of a somewhat rough-and-ready deduction from the perceptibility of c.w. interference. Brief laboratory tests in which a colour bar signal was transmitted through a travelling-wave tube which just conformed with the three-tone test specification suggested that there is no impairment for one relay, a grade 1½ impairment for two relays, rising to about grade 2½ for 5 relays in tandem. The impairment may well be less than this for typical pictures but it must be realised that large areas of fully saturated colour will occur in certain programmes and on certain captions. The luminance and synchronising impairments which might be expected in receivers using synchronous demodulators have been examined theoretically but were not apparent in the tests.

6. Conclusions

The most significant impairment to reception from a chain of tandem relay stations employing travelling-wave tubes in that of the sound/chrominance intermodulation beat produced by the power-dependent phase shift in the travelling-wave tube. Domestic receivers employing synchronous demodulators of the type currently in use exhibit no greater impairment of reception than do those with envelope detectors over the range of phase modulation levels examined in this investigation. Future developments in synchronous detector receivers, in particular any great increase in the effective Q-factor of the demodulating carrier filter, may increase their susceptibility to phase perturbations. It would be desirable for this to be brought to the attention

of receiver manufacturers so that no development of this type is introduced without prior consultation with the broadcasters.

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5. Ibid. Report 405-1, p. 89.
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8. Appendix

8.1. Calculation of the phase perturbation in a given t.w.t. under known operating conditions

The t.w.t. described in Section 2.1 and Fig. 1 had the following dimensions and operation conditions.

f	Vision carrier frequency	500 MHz
V_o	Accelerating potential	3.1 kV
I_b	Beam current	650 mA
l	Helix length	38 cm
P_{rf}	Output power (normal sync level)	20 W

From this we calculate

P_o	Beam power	2 kW
u_o	Initial beam velocity	$3.3 \cdot 10^7$ m/s

$$\text{where } u_o = (2\eta V_o)^{1/2}$$

$$\text{and } \eta = 1.76 \cdot 10^{11} \text{ coulomb/kg for an electron.}$$

From a consideration of the electrodynamics of a beam of electrons passing along the drift tube in a klystron amplifier, Whyte and Eaton³ showed that the phase change of the r.f. signal, using the above notation, is

$$\delta\phi = \frac{\pi fl}{u_o} \frac{P_{rf}}{P_o} \text{ radians}$$

where l is the length of the drift tube and P_{rf} is the r.f. power extracted from the beam at the end of the drift tube.

In a t.w.t. we must allow for the fact that, as the accelerated beam enters the helix, not only is the r.f. power in the beam initially zero, but the initial rate of power transfer back to the helix is also zero. It is reasonable to

postulate that the r.f. power increases as the square of the distance along the helix and that, for a t.w.t., the phase shift is therefore

$$\begin{aligned} \delta\phi' &= \delta\phi \cdot \frac{1}{l} \int_0^l \left(\frac{x}{l}\right)^2 \cdot dx \\ &= \frac{1}{3} \delta\phi \end{aligned}$$

Putting in the figures for the operating conditions, we obtain

$$\delta\phi' = 0.06 \text{ radian}$$

$$= 3.4 \text{ degrees}$$

for a power output of 20 W, in close agreement with the measurement given in Fig. 1.

8.2. Calculation of the spectrum of intermodulation components in the output of a t.w.t. with a known power-dependent phase characteristic

Consider a signal consisting of three steady components representing the vision, colour and sound carriers; this may be written

$$V = v \cos \omega_v t + c \cos \omega_c t + s \cos \omega_s t$$

The power in the envelope of the signal is proportional to

$$\begin{aligned} |V|^2 &= v^2 + c^2 + s^2 + 2vc \cos(\omega_v - \omega_c) t \\ &\quad + 2cs \cos(\omega_c - \omega_s) t \\ &\quad + 2sv \cos(\omega_s - \omega_v) t \end{aligned}$$

Consider now that the signal V is phase-modulated by a linear function of the power $|V|^2$ such that when $v = 1$ represents the signal at sync level (20 Watts), and $c = s = 0$, the phase shift is $\delta\phi'$ as given in Section 8.1. All the components of the signal will be equally phase modulated and we can express the fluctuating quadrature components of the modulated resultant as

$$\begin{aligned} V' &= 2\delta\phi' \left\{ v \cos \omega_v t + c \cos \omega_c t + s \cos \omega_s t \right\} \\ &\quad \left\{ vc \cos (\omega_v - \omega_c)t + cs \cos (\omega_c - \omega_s)t + sv \cos (\omega_s - \omega_v)t \right\} \\ &= \delta\phi' \left[(vc^2 + vs^2) \cos \omega_v t + (cs^2 + cv^2) \cos \omega_c t + (sv^2 + sc^2) \cos \omega_s t \right. \\ &\quad + c^2 v \cos (2\omega_c - \omega_v)t + s^2 c \cos (2\omega_s - \omega_c)t + v^2 s \cos (2\omega_v - \omega_s)t \\ &\quad + v^2 c \cos (2\omega_v - \omega_c)t + c^2 s \cos (2\omega_c - \omega_s)t + s^2 v \cos (2\omega_s - \omega_v)t \\ &\quad \left. + 2vcs \left\{ \cos (\omega_v + \omega_c - \omega_s)t + \cos (\omega_c + \omega_s - \omega_v)t + \cos (\omega_s + \omega_v - \omega_c)t \right\} \right] \end{aligned}$$

The spectrum of these intermodulation products contains nine components at new frequencies as shown in Fig. 2; the third component of the last term of the expression represents the sound/chrominance beat.

$$2\delta\phi' vcs \cos (\omega_s + \omega_v - \omega_c)t$$

Putting in the values of $\delta\phi'$ (−24.5 dB radian), v (−8 dB), c (−17 dB) and s (−7 dB), we have the level of the sound/chrominance beat, relative to sync level, the phase-shift in degrees and the power output.

−50.5 dB for 3.4 degrees at 20 Watts

Correspondingly, a higher phase-shift and power output would give

−52 dB for 4.0 degrees at 23.8 Watts

The measured result of

−52 dB for 3.4 degrees at 20 Watts

is therefore in reasonable agreement with the theory.

The only other new component in the receiver pass-band is given by the middle component of the penultimate term in the intermodulation expression.

$$\delta\phi' c^2 s \cos (2\omega_c - \omega_s)t$$

which, using the same coefficients, gives a result of −65.5 dB and is therefore unimportant.

It may be noted that all the intermodulation terms produced by the process described above are third-order difference terms and there are no harmonics or sum terms. The presence of these would indicate a non-linear mechanism in which the modulation was a function of the instantaneous power, rather than the power in the envelope of the signal as discussed here. These other terms were present at low levels during the experimental work and were found to be caused by non-linearity in the amplifier

driving the t.w.t. but their contribution to the measured levels of the third-order difference terms was found to be negligible.

8.3. Luminance and synchronising errors caused in a synchronous demodulator

The signal received from the n th member of a chain

of tandem relays using travelling-wave tubes can be expressed as $v(t) \exp(jn\phi)$ where ϕ is the phase error introduced by one relay and is a function of the envelope amplitude $v(t)$, as given by Fig. 1. If the signal is applied to a synchronous demodulator in which the local, carrier-frequency signal is produced by filtering and limiting the received carrier component, there will be a transient phase error in the demodulator after any step in the signal amplitude, leading to a transient undershoot in the demodulated step waveform.

The transient error will tend to be greatest when the carrier undergoes a positive step in amplitude (e.g. from white level to black or sync level) and the undershoot in voltage will then be roughly proportional to $v(t)(1 - \cos n\phi)$. The subjective impairment caused by the undershoot will depend on its rate of decay, determined by the bandwidth of the carrier-regenerating circuit and by the type of limiter circuit.

The table opposite shows that, for a chain of five relays, a white-to-black step will give rise to an undershoot of 2% of the step height. The right-hand column shows that, for this type of error to cause a significant impairment, the carrier-regenerating filter would have a bandwidth of 200 kHz or less.

Similarly, a hypothetical step from white level to sync level will give a transient error of 18% of the sync pulse amplitude. This step will not occur in practice, owing to the interruption by the 'front porch' of 1.5 μ s but, if the carrier-regenerating filter bandwidth is reduced to 40 kHz or less, the transient will exist for long enough for the leading edge of the sync pulse to be modulated by the luminance content of the right-hand edge of the picture, leading to possible timing errors in the display.

The figures given opposite are very approximate but serve to indicate the extreme conditions in which impairments to the picture may occur through streaking and line-pulling.

Video Step	Phase shift (5 relays) degrees	Undershoot as a percentage of			Critical bandwidth of carrier regen. channel	
		Carrier level	p-p picture	sync. amp.	kHz	Q
White/black	10	1.5	2.0		200	200
White/sync	17	4.4		18	40	1000

